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Trevor M. Penning,[1] Patrick N. Breysse,[2] Kathleen Gray,[3] Marilyn Howarth,[1] and Beizhan Yan[4]

[1]Center of Excellence in Environmental Toxicology, Perelman School of Medicine, University of Pennsylvania, Philadelphia, Pennsylvania, USA; [2]Division of Environmental Health Engineering, Department of Environmental Health Sciences, The Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland, USA; [3]Center for Environmental Health and Susceptibility, University of North Carolina at Chapel Hill, North Carolina, USA; [4]Lamont-Doherty, Earth Observatory of Columbia University, Palisades, New York, USA

Address correspondence to Trevor M. Penning, Department of Pharmacology, Perelman School of Medicine, University of Pennsylvania, 1315 BRBII/III, 421 Curie Blvd., Philadelphia, PA 19104-6061 USA. Telephone: 215-898-9445. E-mail: penning@upenn.edu

Running title: Research needs on hydraulic fracturing

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Abstract

Background: Unconventional natural gas drilling operations (UNGDO) (which includes hydraulic fracturing and horizontal drilling) supply an energy source which is potentially cleaner than liquid or solid fossil-fuels and may provide a route to energy independence. However, significant concerns have arisen due to the lack of research on the public health impact of UNGDO.

Objectives: Environmental Health Sciences Core Centers (EHSCCs) funded by the National Institute of Environmental Health Sciences (NIEHS) formed a working group to review the literature on the potential public health impact of UNGDO and to make recommendations for needed research.

Discussion: The Inter-EHSCC Working Group concluded that a potential for water and air pollution exists which might endanger public health, and that the social fabric of communities could be impacted by the rapid emergence of drilling operations. The working group recommends research to inform how potential risks could be mitigated.

Conclusions: Exposure and health outcomes research related to UNGDO is urgently needed and community engagement is essential in the design of such studies.

Introduction

Unconventional natural gas drilling operations (UNGDO) (which includes the process of hydraulic fracturing and horizontal drilling) in tight shale formations to extract natural gas creates jobs, provides a potential route to energy independence, and may increase national security through less dependency on foreign oil (Global Insight 2011). The burning of natural gas produces less nitrogen oxides and carbon dioxide than the burning of coal or oil and produces negligible amounts of sulfur dioxide and mercury and thus is a cleaner fossil fuel (see, United States Environmental Protection Agency (US-EPA) Clean-Energy-Gas http://www.epa.gov/cleanenergy/energy-and-you/affect/natural-gas.html and US-EPA Clean-Energy-Coal http://www.epa.gov/cleanenergy/energy-and-you/affect/coal.html). Concurrently, concerns have been raised about the environmental and public health impacts of UNGDO (Union of Concerned Scientists 2013). The industry describes the technology as being well-established and safe (American Petroleum Institute 2014). By contrast some advocacy groups have serious environmental health concerns and suggest that that a moratorium on UNGDO should exist until we learn more (e.g. Physicians for Social Responsibility 2012).

UNGDO have concentrated where large formations of shale exist e.g., Barnett Shale in Texas, Utica Shale in Ohio, and the Marcellus Shale in PA (United States Geological Survey (USGS), 2013). Together, these and other shale gas resources have provided a significant energy resource. For example, the Marcellus Shale contains >84 trillion ft^3 of natural gas which would be sufficient to meet the energy needs of the US for a 2-4 year period (Coleman et al. 2011). However, in areas where UNGDO have occurred there have been incidents of water contamination (Jackson RB et al. 2013), worker exposure to levels of silica dust that exceed the OSHA standards (Esswein et al. 2013), and reports of health impacts among community residents (Bamberger and Oswald 2012; McKenzie et al. 2014). Because of these issues some states e.g. NY have a moratorium on UNGDO while other state legislatures have considered passing strict regulations on the industry (Pless 2011).

In addition, the need for crystalline silica (frac sand) used in the hydraulic fracturing process has expanded mining operations in the upper Mississippi watershed (Wisconsin, Minnesota, and Iowa) and has become a contentious issue in communities due to environmental degradation, lost income from tourism, and risk to respiratory health (State of Wisconsin, 2012).

Based on the level of drilling activity in the Marcellus Shale the Center of Excellence in Environmental Toxicology (CEET), an Environmental Health Sciences Core Center (EHSCC) at the University of Pennsylvania, felt an obligation to address the public health impact of UNGDO on PA citizens. CEET recognized that UNGDO will be part of the energy landscape of the future but that credible science is needed to determine its safety so that there can be evidence-based decision making. CEET realized that the environmental health concerns related to UNGDO could best be addressed by scientists with complementary expertise working together. Concurrently, several Community Outreach and Engagement Cores (COECs) of the EHSCCs identified the growing concerns of citizens and the lack of health-related information. This led to the formation of the Inter-EHSCC working group (see Appendix 1). PubMed citations using the search term “hydraulic fracturing” identified 111 citations during the writing of this article. Only a handful were peer reviewed studies on environmental health and many are cited in this article. In addition, reports by government and health agencies, non-profits and reports from the gas and oil industry were considered. This lead to the unanimous recommendations discussed below.

Discussion

Recommendations for research on water contamination

Groundwater could become polluted due to casement failures and infiltration from soil and surface water during UNGDO. Surface water has the potential to be contaminated by leakage from waste-water impoundments, by incidents during the transport of waste-water and inappropriate discharge from waste-water treatment plants (US-EPA 2011a; Warner et al. 2013). Waste-water consists of the initial flow-back water and the produced-water, which itself is a mixture of spent hydraulic fracturing chemicals as well as contaminants including: total dissolved solids (TDS) that exceed levels found in sea water; aromatic hydrocarbons; heavy metals; and naturally occurring radioactive materials (NORM) that may leach from the shale (Ferrar et al. 2013b; International Association of Oil & Gas Producers, 2002; Rowan et al. 2011).

In Pavillion, Wyoming in 2009, the US-EPA found evidence of groundwater contaminated with benzene, xylenes, gasoline range organics, diesel range organics, and total volatile hydrocarbons in shallow wells that lie above 169 gas-producing wells that were hydrofractured. The pollution was attributed to the thirty-three nearby surface pits used to store drilling waste water (Jackson RE et al. 2013; US-EPA 2011b). The USGS re-sampled the area and confirmed these findings (Wright et al. 2012). However, there were still disputes about whether UNGDO were the source of groundwater contamination because of the lack of baseline water quality measurements (American Petroleum Institute 2012). *Thus base-line ground water quality data should be taken before drilling begins and be monitored over the life-time and abandonment of the gas-producing well.*

Lack of detailed information about the chemicals injected into the shale formations and the composition of the flow-back water makes it difficult to determine whether water quality is affected. A complete inventory of chemical usage, which can exceed >80 additives (Stringfellow et al. 2014) is currently unavailable. The FracFocus web-site (http://fracfocus.org/), a voluntary data-base of chemicals used in the hydraulic fracturing fluid (HF) established by the industry, provides necessary data to map chemical usage by some wells but not all. This represents the first step in determining whether water quality may be affected on a well-by-well basis. Unfortunately, many of the chemicals in use are proprietary and the flow-back and produced water can also contain other contaminants such as polycyclic aromatic hydrocarbons (PAH) and NORM. In the Marcellus formation the level of radioactivity in the produced water was many times higher than allowable for discharge to the environment (Rowan et al. 2011). *To determine whether UNDGO affects water quality full disclosure of the chemicals used in the hydraulic fracturing process must take place so that they can be correlated with measurements of ground and surface water pollutants. The composition of the HF and the produced water must also be analyzed for hazard identification.*

There is a need for sensitive and specific early warning indicators that the ground water has been contaminated. Such indicators would allow researchers and site managers to predict whether UNGDO impacts water quality. Suitable indicators would be chemicals derived from UNGDO that have fast rates of transport, and can be detected easily in field settings. Candidate indicators are methane, ethane, propane, chloride, the sodium to chloride ratio, and the chloride to bromide ratio. Jackson RB et al. 2013 reported that concentrations of methane, ethane and propane in the Marcellus region of PA were higher in homes located < 1 km from drilling sites than in homes farther away. Distance to gas wells was found to be a significant determinant of hydrocarbons in drinking water. However, in some private wells, levels of methane in the drinking water were elevated prior to fracturing (Vidic et al. 2013; Warner et al. 2012); thus methane levels may not be the best indicator. An increase in the ratio of ethane to methane, propane to methane, and chloride to other major anions (e.g. nitrate) could be used as warning indicators of ground water contamination. Alternatively, a unique inert tracer could be added to the HF. *The Inter-EHSCC working group recommends that a validated specific and sensitive indicator of early ground water contamination be identified and universally adopted.*

Knowledge of the fate and transport of pollutants and ground water hydrology under the influence of pressure changes during and after hydraulic fracturing is required to determine whether pollutants can migrate to private or public drinking wells, to identify early warning indicators, and to estimate the transit time of target pollutants and identify suitable remediation strategies. Interaction between the pollutant and particle phase determines the speed of pollutant transport and whether the pollutants can reach drinking-water wells. Groundwater moves slowly, typically in the range of meters per year, depending on characteristics of the aquifer and hydraulic gradients (USGS circular 1186, 2013). Pollutants that can travel to wells within the span of years are those that are persistent, have high solubility and are less-particle reactive. Pollution of surface water (e.g., spills of HF and discharge from waste-water plants) would move faster (in meters per second) and can be affected by reactions between pollutants and the particle phase (USGS, 2007). *Research should be performed to elucidate the fate and transport of ground and surface water pollutants under hydraulic fracturing conditions.*

Assessment of effluent contaminants from waste-water treatment plants discharging Marcellus Shale waste in PA showed that barium, strontium, bromides and chlorides, and TDS exceeded the maximum contaminant level for drinking water (Ferrar et al., 2013b). In 2011, Pennsylvania Department of Environmental Protection (PA-DEP) requested that drilling companies stop disposing waste-water by this method at 15 facilities (PA-DEP 2011). These findings suggest that municipal waste-water treatment plants are unable to deal with contaminants from the produced-water and that water quality from these plants needs to be monitored if these plants are to be used for this purpose (Ferrar et al. 2013b). *The Inter-EHSCC working group recommends that the effluent from a range of waste-water treatment plant technologies be assessed to determine the effectiveness of the technology*.

There is a lack of knowledge of the toxicological properties of the hydraulic fracturing chemicals alone or in complex mixtures. However, the proprietary nature of these chemicals indicates that this may never be known. Knowledge of the chemical additives would enable risk characterization i.e., the identification of no-observed adverse effect levels (NOAEL's), lowest observed adverse effect levels (LOAEL's) for each chemical and reference doses that must be exceeded in order to cause harm in humans. However, because the chemicals are used in a complex mixture, toxicological studies will be required on the mixture itself. The mixture will also have to be fractionated to determine which chemicals or group of chemicals are the most harmful. In this approach compounds can be grouped by chemical similarity or similarity in toxicological effects (European Commission Scientific Committee on Consumer Safety 2011; World Health Organization 2011). Sub-fractions could be triaged using high throughput cell-based screens for genotoxicity, mutagenicity, cytotoxicity and endocrine disrupting properties. Components identified for further study could then be used in acute, intermediate and chronic exposure studies in rodents to identify toxic end-points. *Fundamental research on the toxicology of the individual constituents of HF and the resultant complex mixture should thus be performed.*

Recommendations for research on air pollution

Hazardous air pollutants related to UNGDO include: silica dust from sand-mining, handling, transport and disposition (Esswein et. al. 2013); diesel emissions from delivery trucks, compressor stations, power generators, and drill-rigs (Benbrahim-Talla et al. 2012); VOCs in the flow-back and produced water and their reaction with NOx to increase ground level ozone (Kemball-Cook et. al. 2010); and fugitive gas emissions during the production phase and from well ruptures (Allen et al. 2013). Increased local and regional ambient air pollution has been associated with intensive gas extraction regions (Eaton, 2013; Kargbo et al. 2010; Petron et al. 2012). However, the spatial and temporal release of these pollutants is not well-characterized and will depend on the intensity of the various sources (emission rates) and their locations (e.g., frac sand mines, frac sand transfer stations and truck transport routes to and from the well pad; and the proximity of well pads, produced water containment ponds and waste impoundments to each other and affected communities) and need to be addressed. *Ambient and occupational air-quality should thus be measured at active drilling sites and be compared with base-line measurements in adjacent areas without UNGDO.*

$PM_{2.5}$ in diesel exhaust (from > 2,200 trucks per drill head) can exacerbate respiratory illness and chronic diesel exhaust exposure may increase the risk of lung cancer (Benbrahim-Tallaa et al. 2012). Lung cancer risk was assessed on diesel exhaust emissions that pre-date the 2007 new emission standards. It is unknown how many of the diesel emissions associated with UNGDO meets these new standards, and this should be determined. Diesel pollutants could be related to truck traffic patterns using GIS modeling in order to identify local hot spots and regional impacts that could be mitigated. *The impact of diesel emissions on local air quality should be determined.*

Airborne emissions containing ambient pollutants from UNGDO may impact indoor residential air quality when they penetrate indoor environments. Data on indoor as well as outdoor UNGDO-related pollutant concentrations are thus needed. Residential air quality for people living adjacent to frac sand transfer stations, or those living adjacent to truck transport routes should be compared to those living away from such sources so that base-line data are available. *Residential indoor air quality data for homes potentially impacted by UNGDOs should be compared with those homes not impacted.*

Coal-fired power plants can emit green-house gases, CO_2, as well as SO_x, NO_x, products of incomplete combustion such as PAH, mercury and trace metals. (US-EPA-Clean Energy Coal; http://www.epa.gov/cleanenergy/energy-and-you/affect/coal.html). However, few studies exist to compare levels of air-pollution produced by these plants versus what is produced by a field of natural gas wells. Only when these measurements are made will it be possible to evaluate the potential health risks and benefits of UNDGO compared to the use of coal. *The impact of UNGDO on air pollution should be compared to emissions produced by coal-fired power plants.*

Recommendations for epidemiologic research

Prospective longitudinal epidemiological studies to measure the association between health effects with proximity to UNGDO can only be conducted if the health end-point is known. Health outcomes/utilization data from national and local databases to associate illness and health care encounters with proximity to UNGDO would be a starting point. The working group recognized that baseline data in control communities by census block in which UNGDO is not occurring is key to identifying differences that could become end-points in a prospective epidemiologic study. Using health outcomes data an association between well density and proximity of natural gas wells within a 10-mile radius of maternal residence with prevalence of congenital heart defects in new-borns was observed (Mckenzie et al. 2014). Epidemiologic studies should also include environmental sampling and/or biomonitoring of exposures to demonstrate that there is a dose or exposure dependent association with the end-point(s) being measured. Studies should include occupational exposure and vulnerable populations e.g., pregnant women, children the elderly and asthmatics.

An epidemiologic study linking water pollution from UNGDO to health effects is problematic since the contaminants are not fully known and because of the variability of drinking water sources, pre-existing water quality, chemicals used, temporal relationships, and underlying hydrology. Exposure assessment would require measurement of water quality in communities in which UNGDO is occurring and in adjacent communities where there is no activity to obtain base-line data. Water should be analyzed for suspected contaminants. Biomarkers of exposure to water contamination could rely on measuring blood levels of heavy metals e.g., lead, and biomarkers of VOC's e.g., benzene metabolites. These will be short-lived but measurement of longer-lived biomarkers e.g. serum albumin-benzoquinone adducts is an alternative (Rappaport, et al. 2011). To support a causal relationship between water pollution and health effects a plausible mode-of -action would need to be identified. *An environmental epidemiology study should be performed to determine whether an association exists between health outcomes data and water-quality in private drinking wells in communities with and without hydraulic fracturing.*

An epidemiologic study linking air pollution to health effects is less problematic than those related to water pollution since the air pollutants are known and disease end points are recognized. Recent studies by the National Institute for Occupational Safety and Health (NIOSH) have documented excessive crystalline silica exposures at UNGDO sites (Esswein et al. 2013). In addition, McKenzie et al. (2012) estimated that the increased exposures to airborne hydrocarbons in Garfield County, CO results in a small increased cumulative cancer risk of 10 new cases in one million individuals living within a 0.5 mile of gas-producing wells. Short-, intermediate- and long-term exposures of workers and residents to air pollutants resulting from UNDGO and exacerbation of underlying respiratory illness (e.g., asthma and COPD) and cardiovascular disease (e.g., ischemic heart disease, dysrhythmias, heart failure, and cardiac arrest) may be more sensitive indices of adverse health effects than cancer incidence (Pope et al. 2004). *An environmental epidemiological study should be performed to determine whether air pollution associated with UNDGO increases the incidence of respiratory illness and cardiovascular disease.*

Recommendations on integrating community perspectives in environmental health research

Health impacts and stressors are perceived to exist in communities with UNGDO (Bamberger and Oswald 2012, Ferrar et al. 2013a). Given that elements of a property owner's control may cease once UNGDO begins, these perceptions are consistent with an involuntary risk model, based on a lack of control of an unknown hazard with little opportunity for independent verification of safety (Sjoberg 2000; Slovic 1987;). UNGDO also raises similar issues for impacted communities as other industrial operations in early stages of development: limited data on health indicators and health impacts make it difficult to identify and track health effects, and the latency of effects. Limited to no baseline or monitoring data makes it challenging to track environmental health impacts over time.

Community-based participatory research (CBPR) provides a framework for engaging community members in research and has been effectively applied to a number of environmental health problems (Minkler et al. 2002; O'Fallon and Dearry, 2002). CBPR goes beyond just sharing research results with community members to creating meaningful opportunities for community participation in all stages of research (i.e., project scoping, data collection, analysis and dissemination). *CBPR principles should be embraced in designing and conducting studies on environmental and health impacts of UNGDO so that a range of community perspectives are addressed. All stakeholders (individual/community/industry/advocacy groups/decision makers) should be engaged early to foster multi-directional communication and accountability.*

CBPR requires that study results are communicated in a timely manner to the communities (Chen et al. 2010). A "Community First Communication Model", which shares research findings with the affected community before publishing them in scientific literature, to empower the community by reducing information disparities, is recommended (Emmett et al. 2009). *Communities should be engaged in determining the most effective ways to disseminate research findings and there should be timely and transparent dissemination and access to aggregated data.*

Because the potential exists for lower income communities to bear a greater burden of any negative outcomes of UNGDO, it is important to engage those whose health and environment may be disproportionately impacted by this activity (Adams, 2012). *Thus health disparities due to UNGDO should be addressed in the design of human studies.*

Impacted communities demand transparency in the research process, especially with respect to who is funding the research. This in part stems from mistrust of industry and efforts to limit access to either information on chemicals used in hydraulic fracturing or on-site environmental testing results (Golden Rules Report 2012). *The sources of funding for research on the environmental health impacts of UNGDO need to be openly disclosed.*

In two small, rural communities in Pennsylvania and New York, Brasier et al. (2011) reported that the infrastructure and social services were overwhelmed by the onset of UNGDO and the concomitant population influx. In addition, in a review of medical issues related to UNGDO Saberi (2013) described barriers faced by family physicians, which often are unable to counsel their patients about the effects of environmental exposures related to hydraulic fracturing, due to limited training in occupational and environmental medicine. *The impact on public health and healthcare services of rapid industrialization and training needs of providers should be evaluated.*

Communities have identified a need to understand the regulations that govern UNGDO. Only six states allow health care providers access to proprietary chemical constituents, and four of the six require the health care provider to sign a confidentiality agreement restricting disclosure to others (McFeeley 2012). Denying health care providers access to chemical information for patient care purposes is unprecedented, as is restricting disclosure to individuals who are exposed. *Research should be conducted on how existing regulations impact reporting of environmental health consequences of UNGDO to enable the development of more health-protective regulations.*

Risk perceptions encompass cognitive evaluations of the likelihood of harm as well as emotional responses. Risks that are most feared are those that are unknown, experienced involuntarily, potentially catastrophic, and risky for future generations, all factors which are in play with UNGDO (Sjoberg 2000; Slovic 1987). Having an understanding of the nature of community perceptions on UNGDO will inform risk communication and risk management. It will also identify whether credible sources of information are being used to set view points and will identify critical information gaps. *Research should be conducted on risk perception, including the impacts on community polarization.*

Conclusions

The research recommendations of the inter-EHSCC working group are similar to those proposed by others (Union of Concerned Scientists 2013; Goldstein et al, 2014; Shonkoff et al 2014) with one significant difference in that we advocate for an CBPR approach in communities affected by UNGDO. Implementation of these recommendations would inform the debate on the potential environmental health impacts of UNGDO and lead to decisions by individuals, communities, agencies and industry that would protect human health. Implementation requires dedicated funding sources that are insulated from conflict-of-interest so that the science generated is trustworthy. Funding by federal agencies with research being conducted at academic institutions is one trusted model. Oversight by a single organization would avoid duplication of effort and unnecessary expenditure of resources. There should be harmonization of study designs, data collection and analytical procedures, which may require a data coordination center that could also assess data quality and missing data There should also be a publically available data-repository so that all stakeholders can access data including industry and communities, and appropriate firewalls and limited access should be in place when it comes to patient or population based health data. Implementation of these recommendations would permit a risk assessment of UNDGO, enabling decision makers to identify and reduce the most serious environmental health threats.

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Appendix 1. Inter-EHSCC Working Group Members.

Name	Affiliation
Working Group Members	
Regina Santella, PhD Steven Chillrud, PhD Beizhan Yan, PhD	Columbia Mailman School of Public Health
Douglas Dockery, PhD Ann Backus, MS	Harvard School of Public Health
John Groopman, PhD Patrick Breysse, PhD	Johns Hopkins Bloomberg School of Public Health
David Johnson, MD	MD-Anderson Cancer Center
Max Costa, PhD	New York University
Joseph Beckman, PhD Kim Anderson, PhD	Oregon State University
Helmut Zarbl, PhD	Rutgers University
Suk-mei Ho, PhD Erin Hayes, DPh	University of Cincinnati
Peter Thorne, PhD David Osterberg, PhD	University of Iowa
David Petering, PhD Jeanne Hewitt, PhD, RN	University of Wisconsin - Milwaukee
James Swenberg, PhD Kathleen Gray, MSPH	University of North Carolina at Chapel Hill
Trevor M. Penning, PhD George Gerton, PhD Marilyn Howarth, MD Rey Panettieri, MD Poune Saberi, MD	University of Pennsylvania
Tom Gasiewicz, PhD Katrina Korfmacher, PhD David Rich, ScD, MPH	University of Rochester
Frank Gilliland, PhD Andrea Hricko, MPH	University of Southern California
Cornelius Elferink, PhD Sharon Petronella, MS, PhD John Sullivan	University of Texas Medical Branch
Terry Kavanaugh, PhD	University of Washington
Affiliate Member	
Lias Mckenzie, PhD, MPH	University of Colorado School of Public Health
Ex-Offico Members	
Leslie Reinlib, PhD	Program Director, NIEHS
Liam O'Fallon, MA	Program Analyst, NIEHS